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Airborne Submillimeter Spectroscopy

Contents

1	Introduction	1
2	Coherent Detection	1
3	SIS Receivers	2
4	Development of NbTiN SIS mixers	3
4.1	Quasioptical mixers	3
4.2	Normal metal tuning circuits	4
4.3	NbN films and SIS mixer measurements	5
4.4	NbTiN Films and SIS Tuning Circuits	8
4.5	SIS mixers with NbTiN ground planes	9
4.6	FTS measurements of all-NbTiN devices	9
4.7	SIS mixers with NbTiN/MgO/NbTiN and Nb/AlN/NbTiN junctions	10
5	Conclusions	11
6	References	11
7	List of Publications	15

1 Introduction

This is the final technical report for NASA-Ames grant NAG2-1068 to Caltech, entitled “Airborne Submillimeter Spectroscopy”, which extended over the period May 1, 1996 through January 31, 1998. The grant was funded by the NASA airborne astronomy program, during a period of time after the Kuiper Airborne Observatory was no longer operational. Instead, this funding program was intended to help develop instrument concepts and technology for the upcoming SOFIA (Stratospheric Observatory for Infrared Astronomy) project. SOFIA, which is funded by NASA and is now being carried out by a consortium lead by USRA (Universities Space Research Association), will be a 747 aircraft carrying a 2.5 meter diameter telescope. The purpose of our grant was to fund the ongoing development of sensitive heterodyne receivers for the submillimeter band (500–1200 GHz), using sensitive superconducting (SIS) detectors. In 1997 July we submitted a proposal to USRA to construct a heterodyne instrument for SOFIA. Our proposal was successful [1], and we are now continuing our airborne astronomy effort with funding from USRA. A secondary purpose of the NAG2-1068 grant was to continue the analysis of astronomical data collected with an earlier instrument which was flown on the NASA Kuiper Airborne Observatory (KAO). The KAO instrument and the astronomical studies which were carried out with it were supported primarily under another grant, NAG2-744, which extended over October 1, 1991 through January 31, 1997. For a complete description of the astronomical data and its analysis, we refer the reader to the final technical report for NAG2-744, which was submitted to NASA on December 1, 1997. Here we report on the SIS detector development effort for SOFIA carried out under NAG2-1068. The main result of this effort has been the demonstration of SIS mixers using a new superconducting material, niobium titanium nitride (NbTiN), which promises to deliver dramatic improvements in sensitivity in the 700–1200 GHz frequency range.

In section 2, we review the general motivation for using coherent detection in the submillimeter and far-infrared. The present status of Superconductor-Insulator-Superconductor (SIS) tunnel junction receivers is briefly discussed in section 3, and is followed by a thorough technical discussion of our work on NbTiN SIS mixers in section 4.

2 Coherent Detection

Technology for sensitive coherent detection in the submillimeter and far-infrared continues to be developed rapidly, driven by the needs of a number of astronomical projects including the next generation NASA airborne observatory, SOFIA (Stratospheric Observatory for Infrared Astronomy). See reference [2] for a recent general review of the techniques for coherent detection in the submillimeter band. A coherent detection system is essentially a radio receiver: the weak astronomical signal is combined with a more powerful monochromatic “local oscillator” signal in a sensitive detector, which produces microwave beat frequencies that

can be spectrally analyzed using conventional microwave electronics. Coherent detection is especially useful for high resolution spectroscopy, where resolutions better than 1 km/s are necessary for resolving doppler-broadened spectral lines from galactic objects. Such high spectral resolution ($\lambda/\Delta\lambda \sim 10^6$) is very difficult to obtain using optical filters preceeding direct detectors. However, quantum mechanics imposes an ultimate limit on the sensitivity of coherent systems. This “quantum limit” can exceed the photon fluctuations of the background radiation, which sets the fundamental sensitivity limit for direct detection, particularly in the cases that the thermal background is very low (as occurs in the Wien limit $h\nu \gg kT$). For SOFIA, which will have a total emissivity (telescope plus atmosphere) around 30%, and a physical temperature around 250 K, coherent detection is expected to be competitive with direct detection well into the far-infrared region, $\lambda \sim 150\mu\text{m}$.

Two types of detectors (or “mixers”) are being developed for the far-infrared wavelength region, both of which use superconductors. The first type of detector is based on SIS (superconductor-insulator-superconductor) tunnel junctions. SIS devices are well understood, and in theory can reach the quantum limit of sensitivity. In practice, excellent performance is achieved up to 700 GHz using niobium devices, and the measured receiver sensitivities are close to the fundamental quantum limit (i.e. within factors of a few). The work supported by this grant (NAG2-1068) has shown that similar performance up to 1200 GHz should be possible using SIS devices made using a new superconducting material – niobium titanium nitride (NbTiN). For yet higher frequencies, a newer type of device has recently been developed – the superconducting hot electron bolometer (HEB). The experimental results to date have been very encouraging, with low-noise mixing demonstrated up to 2500 GHz; however, the measured sensitivities are still far from the quantum limit. It therefore appears to be important to push the frequency limit of the more sensitive SIS technology as high as possible.

3 SIS Receivers

The development of fabrication techniques for producing small area, high current density superconductor-insulator-superconductor (SIS) tunnel junctions integrated with thin-film microstrip tuning circuits has resulted in a dramatic improvement in the sensitivity of heterodyne receivers in the 100–1000 GHz range[2]. At present, the most commonly used superconducting material is niobium (Nb), which has a transition temperature of 9.2 K. In theory, the sensitivity of SIS mixers can approach the quantum limit $T_N = h\nu/k_B$; in practice, the best results below the 700 GHz gap frequency of niobium are within a factor of 2–5 of this limit. However, the noise of sensitive receivers is actually often dominated by other factors such as optical losses, thermal noise, and IF amplifier noise, rather than by the noise in the SIS mixer itself. The situation changes dramatically above 700 GHz, at which point the niobium tuning circuits become very lossy since the photon energy is large enough to break

Cooper electron pairs ($h\nu > 2\Delta$). At these frequencies, the performance is limited by the circuit losses, even when high conductivity normal metals such as aluminum are used for the tuning circuit [3, 4, 5, 6] in place of niobium. Niobium titanium nitride (NbTiN) appears to be a good superconducting material for higher frequencies, since NbTiN has a larger critical temperature (16 K) and gap frequency (1200 GHz) than niobium, and high quality NbTiN films can be fabricated. Under this grant, we have made initial SIS mixer measurements using tuning circuits made with superconducting NbTiN films and tunnel junctions.

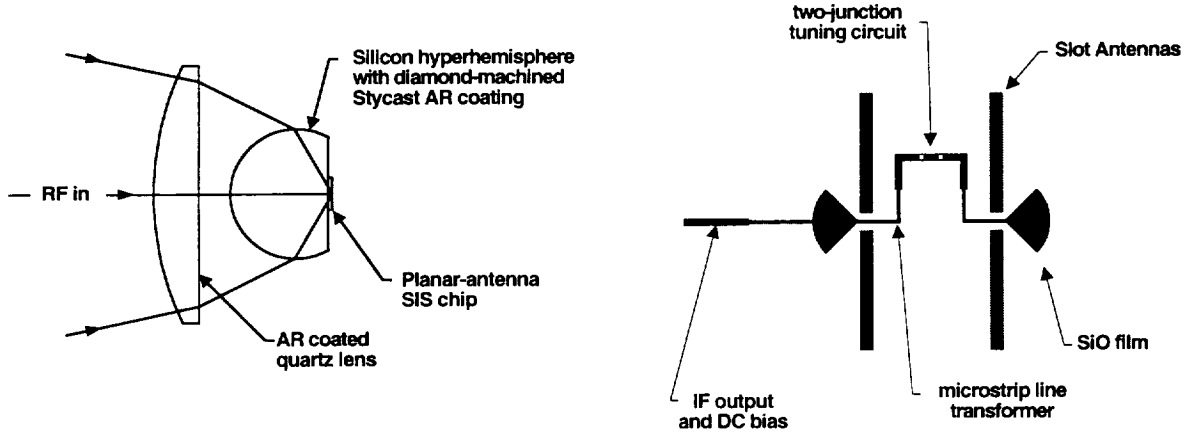


Figure 1: Our quasi-optical mixer design. **Left:** the optical configuration uses an antireflection-coated hyperhemispherical silicon lens to focus the submillimeter radiation onto the SIS chip; **Right:** the SIS chip consists of a twin slot antenna, a microstrip transformer, and a tuning circuit which uses two SIS junctions.

4 Development of NbTiN SIS mixers

4.1 Quasioptical mixers

The measurements were performed using our standard quasioptical mixer configuration (Fig. 1). In this design, a planar twin slot antenna[7] is lithographically fabricated along with the SIS junctions on a silicon substrate, and then this integrated “chip” is placed behind a hyperhemispherical lens which focuses the incoming radiation onto the antenna. Because the dielectric constant of silicon is fairly high ($\epsilon_r = 11.5$), the twin slot antenna has a forward efficiency of 90%. The reflection loss from the surface of the silicon lens is eliminated using a quarter-wavelength anti-reflection coating [8] of alumina-loaded epoxy, which has an effective dielectric of about $\epsilon_r = 4$. The coating is cut to the correct thickness on an optical diamond-turning machine. This method results in smooth, very rugged,

cryogenically cycleable coatings which have excellent optical performance.

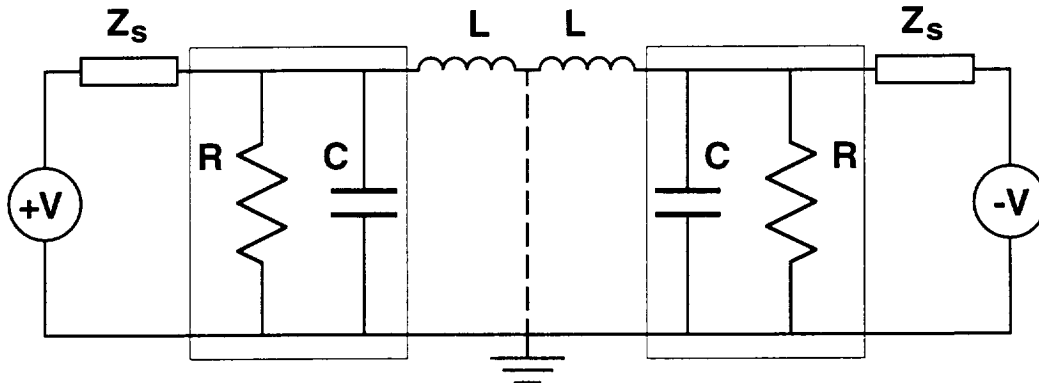


Figure 2: The equivalent circuit for our SIS mixer design. The junctions can be idealized as simple parallel RC circuits. The physical spacing between the junctions determines the effective tuning inductance L . The slot antennas and microstrip transformers can be considered to be generators with a complex source impedance Z_s ; the two generators are 180° out of phase due to the symmetry of the coupling to the twin-slot antenna.

One of the crucial aspects of our SIS mixer design is the tuning circuit which resonates the SIS junction capacitance and matches the junction impedance to the slot antenna. We use a two-junction tuning circuit[9], in which the two junctions are separated by a section of microstrip line which serves as a tuning inductance (Fig. 2). This design has been extensively characterized using niobium devices[10]. Fourier transform spectrometer (FTS) measurements of the direct-detection frequency response of the niobium devices agree quite well with our circuit simulations. The circuit simulator[11] includes the complex frequency-dependent impedance of the slot antenna as well as the impedance and propagation characteristics of the superconducting microstrip lines used in the transformers and tuning inductance. The microstrip model[7] includes dispersion and fringing effects[12] and incorporates the surface impedance as calculated using the Mattis-Bardeen theory[13] in the local limit.

4.2 Normal metal tuning circuits

As shown in Fig. 3, a microstrip line made with normal-metal aluminum films has substantially less loss than a corresponding niobium line at frequencies above 800 GHz. SIS mixers using aluminum microstrip circuits with niobium tunnel junctions have in fact been demonstrated at frequencies over 1 THz[3, 4, 5, 6] with noise temperatures somewhat below 1000 K (DSB). Although these mixers are substantially less sensitive than SIS mixers below 700 GHz, they are nonetheless the most sensitive heterodyne devices demonstrated to date

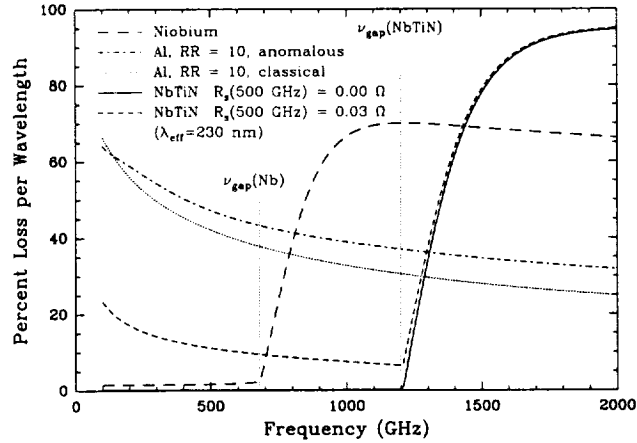


Figure 3: Calculated losses for thin-film microstrip transmission lines used in SIS mixer tuning circuits for various conductors, including NbTiN. The microstrip width is $5\text{ }\mu\text{m}$, and the dielectric is 400 nm SiO ($\epsilon = 5.6$).

at 1 THz . Not surprisingly, detailed analyses of the mixer performance[4, 5] indicate that the tuning circuit loss is the primary limitation on the performance.

Figure 4 shows the results of Fourier transform spectrometer measurements on a set of SIS devices with aluminum microstrip tuning circuits.[4] These results demonstrate that the tuning circuits have very broad resonances, around 400 GHz wide, which indicates a rather low Q -factor due to the loss in the aluminum lines. Furthermore, the vertical scale in these plots gives the calculated RF coupling efficiency. At 1 THz , the coupling efficiency is only 20% , indicating that 80% of the signal power received by the twin-slot antenna and injected into the microstrip circuit is dissipated instead of being detected by the tunnel junction. Clearly, the performance of SIS mixers at 1 THz could be improved dramatically if a low-loss conductor were available.

4.3 NbN films and SIS mixer measurements

Niobium Nitride (NbN) is a very well known superconductor. NbN films can be fabricated in a variety of ways, the most common method being reactive magnetron sputtering, and the resulting films display a large range in characteristics[14, 15, 16, 17, 18, 19]. In particular, the substrate temperature during deposition has a strong influence on the quality of NbN films, as characterized by the normal-state resistivity ρ_n or the magnetic penetration depth λ . Normal-state resistivities as low as $25\text{ }\mu\Omega\text{ cm}$ have been obtained, using heated ($\sim 350\text{ C}$) silicon substrates coated with SiC buffer layers[17]. More typically, resistivities of $60\text{ }\mu\Omega\text{ cm}$ are obtained on heated MgO substrates. For unheated substrates, resistivities over $140\text{ }\mu\Omega\text{ cm}$ are common, although lower values have been obtained in some cases[18]. Low-resistivity

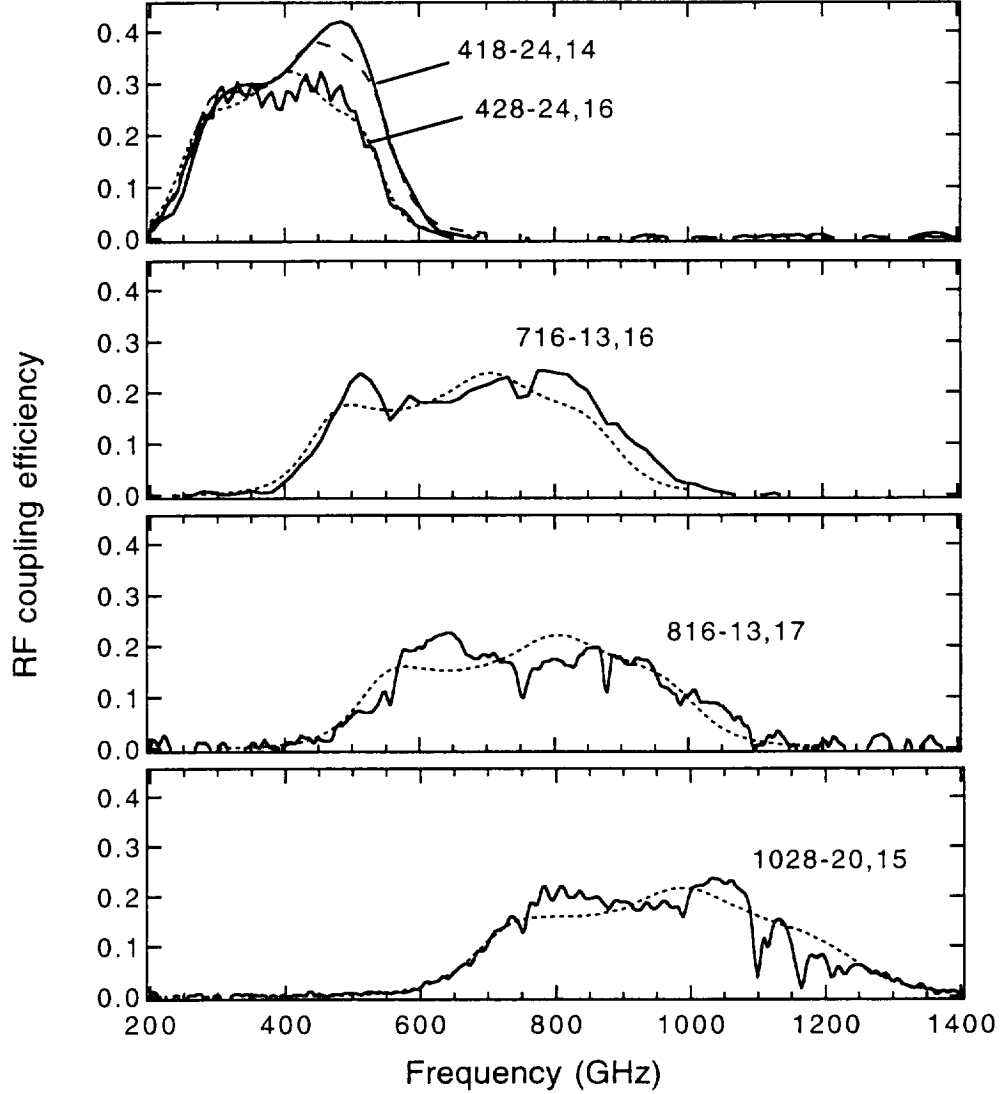


Figure 4: Measured and calculated frequency response for a series of SIS mixer chips fabricated with normal metal aluminum tuning circuits. Since we cannot calibrate the absolute response, the Fourier transform spectrometer (FTS) measurements are scaled (vertically) to match the circuit simulations. The “notches” in the response above 1 THz are due to absorption by residual water vapor in our nitrogen-flushed system.

films most often show a decreasing resistance with temperature, while high-resistivity films show a constant or even slightly increasing resistance with temperature. These variations in film properties are associated with variations in the microstructure of the films.

A number of measurements of the electrodynamic properties of NbN thin films have been reported[20, 21, 22]. These measurements, which were performed with a variety of techniques

over different frequency ranges, are in reasonable agreement if films with similar resistivities are compared. Empirically, the resistivity, critical temperature, and magnetic penetration depth obey the BCS relation[20]

$$\lambda \approx \left[\frac{\rho(\mu\Omega \text{ cm})}{T_c(\text{K})} \right]^{1/2} \times 100 \text{ nm} \quad (1)$$

For example, for $T_c = 16 \text{ K}$ and $\rho = 60 \mu\Omega \text{ cm}$, the calculated penetration depth $\lambda = 200 \text{ nm}$ agrees well with the measured value[23]. Below the gap frequency, the surface reactance of a superconductor is inductive and is given by $X_s = \omega\mu_0\lambda$. On the other hand, the surface resistance R_s is difficult to predict, and is often not well described by simple theory. For thin film microstrip lines, which have dielectric thicknesses $t < 2\lambda$, the surface resistance must obey

$$R_s \ll \eta_0 \frac{\lambda}{\lambda_0} = 0.25 \Omega \left[\frac{1 \text{ THz}}{\nu} \right] \left[\frac{\lambda}{200 \text{ nm}} \right] \quad (2)$$

in order for the microstrip line to have low loss per wavelength. Here $\eta_0 = 377 \Omega$ and λ_0 is the free-space wavelength. For an SIS mixer, in which a microstrip circuit tunes out the junction capacitance, the limit on the surface resistance is more restrictive:

$$R_s \ll \eta_0 \frac{\lambda}{\lambda_0} \frac{2\pi}{Q} = \eta_0 \frac{\lambda}{c\tau} \quad (3)$$

where $\tau = R_N C$ is the time constant of the SIS junction and $Q = \omega\tau = \omega R_n C$. For Nb/Al-oxide/Nb junctions with $R_N A = 20 \Omega \mu\text{m}^2$ and $C_s = 80 \text{ fF } \mu\text{m}^{-2}$, and taking $\lambda = 200 \text{ nm}$, this limit is $R_s \ll 0.15 \Omega$.

Kohjiro, Kiryu, and Shoji[22] found that the surface resistance R_s of superconducting NbN in the 200–1000 GHz band was strongly correlated with the normal-state resistivity: high temperature, “epitaxially” grown films had a surface resistance that was an order of magnitude lower than unheated “polycrystalline” films. In fact, their data indicate that the surface resistance of the polycrystalline films rises very rapidly with frequency, and is quite large at 1 THz, around $R_s \approx 0.5 \Omega$. Unfortunately, SIS mixer devices are most often made with the polycrystalline films, since high temperature film growth is usually not compatible with high current density SIS tunnel junction fabrication. Also, it is difficult to obtain low resistivity “epitaxial” growth on top of the SiO or SiO₂ dielectric films used for the microstrip transmission lines.

The performance of NbN SIS mixers have been measured by several groups[24, 25, 26, 27]. Recently[26, 27], noise temperatures around 200 K have been obtained at 300 GHz. SIS mixers using niobium devices achieve substantially lower noise, by at least a factor of 4. Although excess loss in the NbN tuning circuits may be responsible for some of this discrepancy, other factors such as optical losses, mixer design, and excess shot noise in NbN junctions[28] may contribute as well. The performance of NbN SIS mixers appears to

deteriorate rapidly at higher frequencies[25], as would be expected given the large surface resistance of polycrystalline NbN films. Measurements on a wider variety of devices would be desirable, especially those fabricated with high quality films.

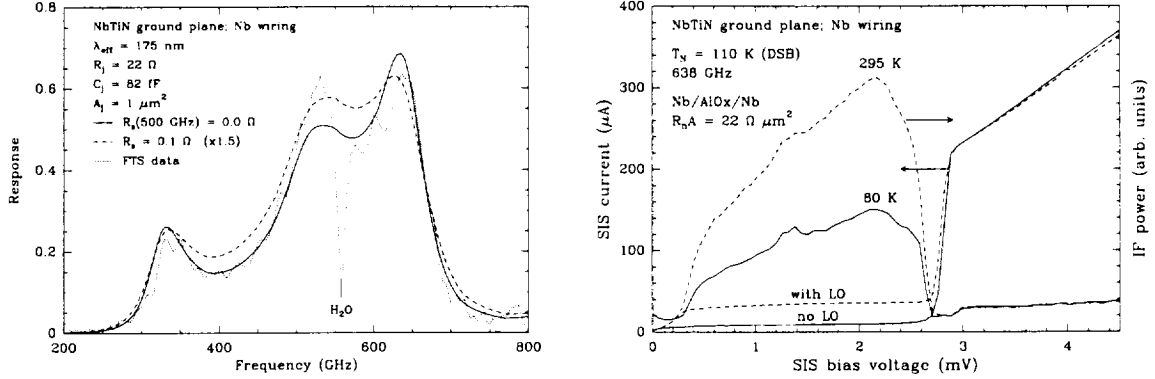


Figure 5: Measurements of a twin-slot SIS mixer with a NbTiN ground plane, Nb/AlO_x/Nb junction, and a niobium wiring layer. **Left:** The direct-detection frequency response measured with our FTS. A magnetic penetration depth of $\lambda \approx 175$ nm is inferred for the NbTiN ground plane. **Right:** a heterodyne hot/cold load response measurement at 638 GHz. The uncorrected receiver noise temperature is 110 K (DSB), which is comparable to the best results obtained at this frequency with all-niobium SIS mixers.

4.4 NbTiN Films and SIS Tuning Circuits

An interesting alternative to NbN is niobium titanium nitride, Nb_{1-x}Ti_xN. In fact, superconducting NbTiN films were produced thirty years ago in an early study of NbN film deposition[29]. More recently, NbTiN films have been investigated for use in RF cavities for particle accelerators[30]. This study showed that for $x \leq 0.4$, the NbTiN films have critical temperatures similar to NbN, or $T_c \approx 16$ K, which is substantially higher than niobium ($T_c = 9.2$ K). However, the normal-state resistivity of the films drops rapidly as the titanium fraction x is increased: NbTiN films grown on *unheated* substrates often have similar (or lower) resistivity than NbN films grown on *heated* substrates. This might have been expected, since the resistivity of TiN films is quite low[31]. Similar results were obtained independently at JPL during the process of characterizing and optimizing NbTiN film deposition. In addition, tunnel junctions coupled to NbTiN microstrip resonators were fabricated at JPL, which showed resonant features at bias voltages in excess of 2 mV. These measurements indicated that the loss of NbTiN at 1 THz should be quite low, and encouraged us to attempt SIS mixer measurements using this material.

4.5 SIS mixers with NbTiN ground planes

As a first step, we fabricated and tested twin-slot devices which used NbTiN films as the ground plane, along with Nb/Al-oxide/Nb junctions and a Nb wiring layer. We used our existing lithography masks, which had been designed for niobium[10]. Because the magnetic penetration depth of NbTiN is much larger than for niobium, the tuning inductance is larger, and the resonant frequency of the circuit is reduced. In an attempt to compensate for this effect, we selected a device nominally designed for 550 GHz but whose junction areas ($1 \mu\text{m}^2$) were much smaller than the nominal area for the design ($1.7 \mu\text{m}^2$). As shown in Figure 5, the resonance frequency actually was shifted *above* 550 GHz, since the small junction areas overcompensated for the increase in penetration depth. A very low value of 175 nm was obtained for the penetration depth of NbTiN by matching the circuit simulations to the FTS data. In addition, heterodyne measurements at 638 GHz, near the peak of the FTS response, gave an uncorrected noise temperature of 110 K (DSB), which is certainly an impressive result at this frequency. This low noise temperature indicates that the loss of the NbTiN film must be quite low, although it is difficult to give a useful quantitative estimate of the loss from the noise temperature alone.

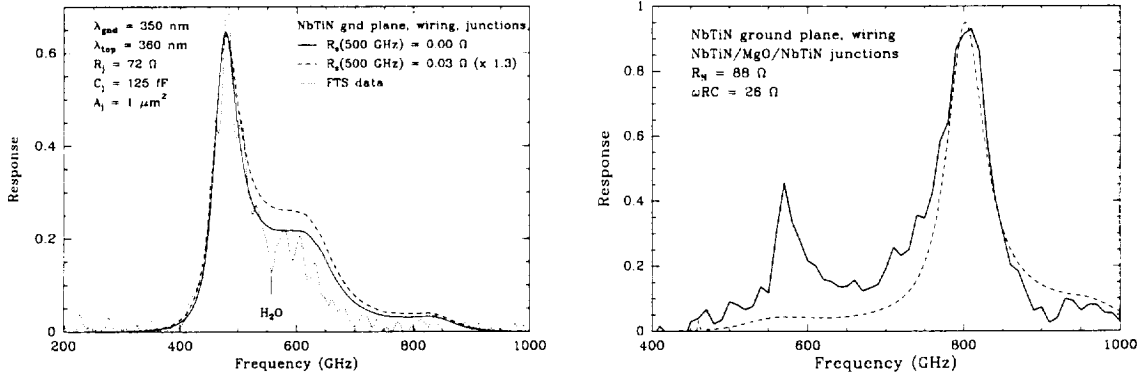


Figure 6: Measured and calculated frequency responses for SIS tuning circuits using NbTiN ground planes and wiring layers, and NbTiN/MgO/NbTiN junctions. **Left:** The narrow width of the resonance implies a limit of 0.03Ω to the excess surface resistance at 500 GHz. **Right:** The resonance width remains quite narrow at 800 GHz. At present, we do not fully understand the origin of the secondary peak at 570 GHz.

4.6 FTS measurements of all-NbTiN devices

The positive results obtained with NbTiN ground planes encouraged us to fabricate and measure devices which use NbTiN in the wiring layer as well as the ground plane. In general, it is substantially more difficult to grow a high-quality film for the wiring layer, since the substrate cannot be heated significantly without damaging the tunnel junctions,

and since the film is grown on top of the SiO film used for the junction passivation and microstrip dielectric material. Figure 6 shows some representative results. The evidence that the loss of the NbTiN films is low in these devices comes primarily from the *shape* of the measured frequency response of SIS tuning circuits. Depending on the design and the fabrication parameters, the tuning circuit may produce a high- Q resonance, whose width provides direct information on the loss of the NbTiN material. As is clear from Figures 4 and 6, the NbTiN SIS circuits have much narrower resonances than the circuits with normal-metal aluminum microstrip lines. Thus, we can be quite certain that the losses in the NbTiN films are substantially lower than for aluminum films in the 500–800 GHz frequency range. At 500 GHz, we estimate that any *excess* surface resistance in the NbTiN films cannot exceed $0.03\ \Omega$, which is substantially below the surface resistance measured at this frequency by Kohjiro et al.[22] for unheated polycrystalline NbN films. At 800 GHz, our simulations indicate that the excess surface resistance of the wiring layer is well below $0.1\ \Omega$ if we assume that the ground plane is essentially lossless.

Figure 6 also indicates some of the challenges we face. The resonances are often shifted down from the design frequency due to variations in the NbTiN film deposition process. Compared to our best films, a non-ideal film will generally have a lower critical temperature along with a larger normal-state resistivity. According to equation 1, both of these effects result in an increase in the penetration depth λ . In fact, as shown in Fig. 6, the NbTiN penetration depth can be quite large (350 nm) when the NbTiN deposition conditions are not optimum. Additionally, in some cases the measured frequency responses show secondary peaks at lower frequencies, which are not predicted by our simulations. We suspect that these may be related to modifications that were made in the design of the antenna coupling stubs and the IF output line. Finally, the I - V curves of the devices often show series weak-link behavior at high currents. These weak links are most likely produced in the region where the NbTiN wiring layer crosses over the edges of the ground plane at the slot antenna. We have some evidence from SIS heterodyne testing that these weak links are capable of absorbing RF radiation from the antenna, which reduces the LO pump level and the heterodyne response, but does not affect the width of the direct-detection resonance measured with the FTS.

4.7 SIS mixers with NbTiN/MgO/NbTiN and Nb/AlN/NbTiN junctions

We have obtained good mixer results using SIS devices with all-NbTiN tuning circuits at frequencies around 600 GHz (Fig. 7), with noise temperatures around 200 K (DSB). Devices with three different junction types have been fabricated: Nb/Al-Oxide/Nb, Nb/AlN/NbTiN, and NbTiN/MgO/NbTiN. Figure 7 shows typical pumped and unpumped I - V curves for the junctions with AlN and MgO tunnel barriers. The Nb/AlN/NbTiN devices are especially promising since they combine the sharp I - V behavior usually associated with niobium junctions but have a substantially larger gap voltage, around 3.5 mV, compared to 2.9 mV for

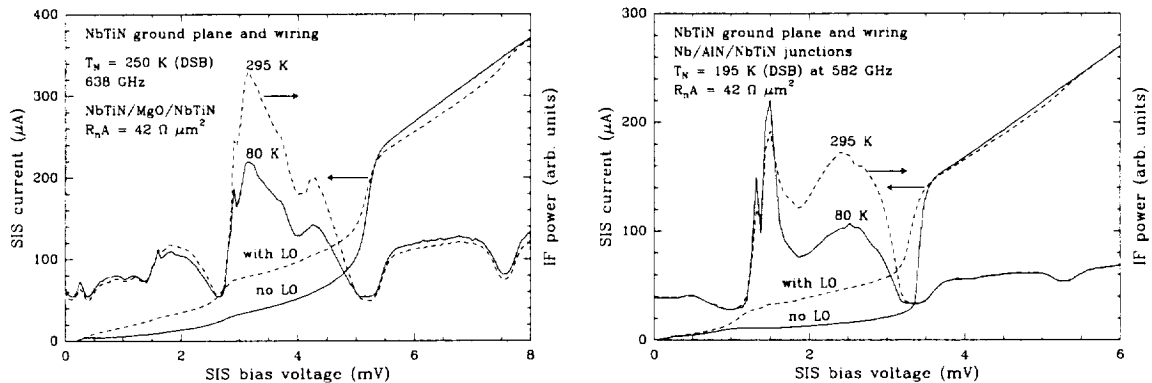


Figure 7: 600 GHz heterodyne measurements on SIS mixers using NbTiN ground planes and wiring layers. **Left:** A device with NbTiN/MgO/NbTiN junctions; **Right:** A device with Nb/AlN/NbTiN junctions.

niobium. This is particularly important for mixers operating near 1 THz, since the 0.6 mV increase in gap voltage translates into a 1.2 mV increase in the available voltage bias range. We hope to extend our mixer measurements to 800 GHz in the near future.

5 Conclusions

Our measurements indicate that NbTiN films will allow very low noise SIS mixers to be developed for frequencies near 1 THz. At the minimum, we can expect a factor of two improvement over existing 1 THz SIS mixers, by using high quality NbTiN ground planes and aluminum wiring layers. This approach should yield noise temperatures around 400 K (DSB)[3] at 1 THz. Low loss all-NbTiN devices may offer even better performance, perhaps as low as 200 K (DSB).

6 References

- [1] J. Zmuidzinas, G. Blake, J. Keene, T. Phillips, N. Erickson, P. Goldsmith, A. Harris, M. Morris, W. Langer, H. Leduc, and W. McGrath, “A submillimeter/far-IR heterodyne receiver for SOFIA,” #09.06, *Bull. American Astron. Soc.*, vol. 191, Dec. 1997.
- [2] J. Carlstrom and J. Zmuidzinas, “Millimeter and submillimeter techniques,” in *Review of Radio Science 1993–1996* (W. R. Stone, ed.), pp. 839–882, Oxford University Press, 1996.

- [3] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Low-noise 1 THz niobium superconducting tunnel junction mixer with normal metal tuning circuit," *Appl. Phys. Lett.*, vol. 68, pp. 1714–1716, 1996.
- [4] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Quasi-optical SIS mixers with normal metal tuning structures," *IEEE Trans. Applied Superconductivity*, vol. 7, pp. 3584–3588, 1997.
- [5] P. Dieleman, T. M. Klapwijk, J. R. Gao, and H. van de Stadt, "Analysis of Nb superconductor–insulator–superconductor tunnel junctions with Al striplines for THz radiation detection," *IEEE Trans. Applied Superconductivity*, vol. 7, pp. 2566–2569, 1997.
- [6] T. M. Klapwijk, P. Dieleman, and M. W. M. DeGraauw, "Pushing the operating range of SIS mixers into the THz regime," *Supercon. Sci. Tech.*, vol. 12, pp. 876–879, 1997.
- [7] J. Zmuidzinas and H. G. LeDuc, "Quasi-optical slot antenna SIS mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-40, pp. 1797–1804, 1992.
- [8] J. Zmuidzinas, N. G. Ugras, D. Miller, M. C. Gaidis, and H. G. LeDuc, "Low noise slot antenna SIS mixers," *IEEE Trans. Applied Superconductivity*, vol. 5, pp. 3053–3056, 1995.
- [9] J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, "Two-junction tuning circuits for submillimeter SIS mixers," *IEEE Transactions on Microwave Theory Techniques*, vol. 42, pp. 698–706, Apr. 1994.
- [10] M. C. Gaidis, H. G. LeDuc, M. Bin, D. Miller, J. A. Stern, and J. Zmuidzinas, "Characterization of low-noise quasi-optical SIS mixers for the submillimeter band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, pp. 1130–1139, 1996.
- [11] M. Bin, *Low-Noise Terahertz Niobium SIS Mixers*. PhD thesis, California Institute of Technology, 1997.
- [12] E. Hammerstad and O. Jensen, "Accurate models for microstrip computer-aided design," *MTT-S Int. Microwave Symp. Dig.*, pp. 407–409, 1980.
- [13] D. C. Mattis and J. Bardeen, "Theory of the anomalous skin effect in normal and superconducting metals," *Phys. Rev.*, vol. 111, pp. 412–417, 1958.
- [14] M. Gurvitch, J. P. Remeika, J. M. Rowell, J. Geerk, and W. P. Lowe, "Tunneling, resistive, and structural study of NbN and other superconducting nitrides," *IEEE Trans. Magnetism*, vol. 21, pp. 509–513, 1985.

- [15] J. A. Stern and H. G. LeDuc, "Characterization of NbN films and tunnel junctions," *IEEE Trans. Magnetics*, vol. 27, pp. 3196–3199, 1991.
- [16] A. Shoji, "Fabrication of all-NbN tunnel junctions using single crystal NbN films for the base electrodes," *IEEE Trans. Magnetics*, vol. 27, pp. 3184–3187, 1991.
- [17] A. Shoji, S. Kiryu, and S. Kohjiro, "Epitaxial growth of NbN and NbC_xN_{1-x} films on 3C-SiC film-covered Si wafers," *IEEE Trans. Applied Superconductivity*, vol. 5, pp. 2396–2399, 1995.
- [18] Z. Wang, A. Kawakami, and Y. Uzawa, "Superconducting properties and crystal structures of niobium nitride thin films deposited at ambient substrate temperature," *J. Appl. Phys.*, vol. 79, pp. 7837–7842, 1996.
- [19] V. Boffa, U. Gambardella, V. Marotta, A. Morone, F. Murtas, S. Orlando, and G. P. Parisi, "NbN superconducting thin films grown by pulsed laser ablation," *Appl. Surf. Sci.*, vol. 106, pp. 361–364, 1996.
- [20] A. Cucolo, A. Nigro, and R. Vaglio, "Surface impedance of NbN superconducting thin films by Josephson measurements," *J. Low Temp. Phys.*, vol. 69, pp. 363–376, 1987.
- [21] D. E. Oates, A. C. Anderson, C. C. Chin, J. S. Derov, G. Dresselhaus, and M. S. Dresselhaus, "Surface impedance measurements of superconducting NbN films," *Phys. Rev. B*, vol. 43, pp. 7655–7663, 1991.
- [22] S. Kohjiro, S. Kiryu, and A. Shoji, "Surface resistance of epitaxial and polycrystalline NbCN films in submillimeter wave region," *IEEE Trans. Applied Superconductivity*, vol. 3, pp. 1765–1767, 1993.
- [23] B. Komiyama, Z. Wang, and M. Tonouchi, "Penetration depth measurements of single-crystal NbN films at millimeter-wave region," *Appl. Phys. Lett.*, vol. 68, pp. 562–563, 1996.
- [24] W. R. McGrath, J. A. Stern, H. H. S. Javadi, S. R. Cypher, B. D. Hunt, and H. G. LeDuc, "Performance of NbN superconductive tunnel junctions as SIS mixers at 205 GHz," *IEEE Trans. Magnetics*, vol. 27, pp. 2650–2653, 1991.
- [25] H. van de Stadt, J. Mees, Z. Barber, M. Blamire, P. Dieleman, and T. DeGraauw, "Submm heterodyne mixing using NbCN/Nb SIS tunnel junctions," *Int. J. IR and MM Waves*, vol. 17, pp. 91–104, 1996.
- [26] Y. Uzawa, Z. Wang, and A. Kawakami, "Quasi-optical NbN/AlN/NbN mixers in submillimeter-wave band," *IEEE Trans. Applied Superconductivity*, vol. 7, pp. 2574–2577, 1997.

- [27] A. Karpov, B. Plathner, and J. Blondel, "Noise and gain in frequency mixers with NbN SIS junctions," *IEEE Trans. Applied Superconductivity*, vol. 7, pp. 1077–1080, 1997.
- [28] P. Dieleman, H. G. Bukkems, T. M. Klapwijk, M. Schicke, and K. H. Gundlach, "Observation of Andreev reflection enhanced shot noise," *Phys. Rev. Lett.*, vol. 79, pp. 3486–3489, 1997.
- [29] J. R. Gavaler, J. K. Hulm, M. A. Janocko, and C. K. Jones, "Preparation and superconducting properties of thin films of transition metal interstitial compounds," *J. Vac. Sci. Tech.*, vol. 6, pp. 177–180, 1968.
- [30] R. D. Leo, A. Nigro, G. Nobile, and R. Vaglio, "Niobium-titanium nitride thin films for superconducting RF accelerator cavities," *J. Low Temp. Phys.*, vol. 78, pp. 41–50, 1990.
- [31] W. Tsai, M. Delfino, J. A. Fair, and D. Hodul, "Temperature dependence of the electrical resistivity of reactively sputtered TiN films," *J. Appl. Phys.*, vol. 73, pp. 4462–4467, 1993.

7 List of Publications

- [1] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Thz SIS mixers with normal metal Al tuning circuits," *Supercond. Sci. Tech.*, vol. 9, pp. A136–A139, Apr. 1996.
- [2] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Low-noise 1 THz niobium superconducting tunnel junction mixer with normal metal tuning circuit," *Appl. Phys. Lett.*, vol. 68, pp. 1714–1716, 1996.
- [3] M. Bin, M. C. Gaidis, D. Miller, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Design and characterization of a quasi-optical SIS receiver for the 1 THz band," in *The Seventh International Symposium on Space Terahertz Technology: Symposium Proceedings*, (University of Virginia, Charlottesville, VA), pp. 549–560, Mar. 1996.
- [4] M. C. Gaidis, H. G. LeDuc, M. Bin, D. Miller, J. A. Stern, and J. Zmuidzinas, "Characterization of low-noise quasi-optical SIS mixers for the submillimeter band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, pp. 1130–1139, 1996.
- [5] J. Zmuidzinas, "Recent progress in submillimeter heterodyne receiver development," in *Submillimeter and far-infrared space instrumentation: 30th ESLAB Symposium Proceedings*, vol. ESA SP-388, (ESTEC, Noordwijk, The Netherlands), pp. 151–154, Dec. 1996.
- [6] J. Carlstrom and J. Zmuidzinas, "Millimeter and submillimeter techniques," in *Review of Radio Science 1993–1996* (W. R. Stone, ed.), pp. 839–882, Oxford University Press, June 1996.
- [7] M. C. Gaidis, M. Bin, D. Miller, J. Zmuidzinas, H. LeDuc, and J. Stern, "Characterization of submillimeter quasi-optical twin-slot double-junction SIS mixers," *Supercond. Sci. Tech.*, vol. 9, pp. A133–A135, Apr. 1996.
- [8] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Quasi-optical SIS mixers with normal metal tuning structures," *IEEE Trans. Applied Superconductivity*, vol. 7, pp. 3584–3588, June 1997.
- [9] J. W. Kooi, J. A. Stern, G. Chattopadhyay, H. G. LeDuc, B. Bumble, and J. Zmuidzinas, "Low-loss NbTiN films for THz SIS mixer tuning circuits," in *The Eighth International Symposium on Space Terahertz Technology: Symposium Proceedings* (R. Blundell and E. Tong, eds.), (Harvard-Smithsonian Center for Astrophysics, Cambridge, MA), pp. 310–318, 1997.

- [10] J. Zmuidzinas, G. Blake, J. Keene, T. Phillips, N. Erickson, P. Goldsmith, A. Harris, M. Morris, W. Langer, H. Leduc, and W. McGrath, "A submillimeter/far-IR heterodyne receiver for SOFIA," #09.06, *Bull. American Astron. Soc.*, vol. 191, Dec. 1997.
- [11] J. W. Kooi, J. A. Stern, G. Chattopadhyay, H. G. LeDuc, B. Bumble, and J. Zmuidzinas, "Low-loss NbTiN films for THz SIS mixer tuning circuits," in *Ninth International Symposium on Space Terahertz Technology: Symposium Proceedings*, (Jet Propulsion Laboratory, Pasadena, CA), pp. 283-294, Mar. 1998.
- [12] J. A. Stern, B. Bumble, H. G. LeDuc, J. W. Kooi, and J. Zmuidzinas, "Fabrication and DC characterization of NbTiN based SIS mixers for use between 600 and 1200 GHz," in *Ninth International Symposium on Space Terahertz Technology: Symposium Proceedings*, (Jet Propulsion Laboratory, Pasadena, CA), pp. 305-313, Mar. 1998.
- [13] G. Chattopadhyay and J. Zmuidzinas, "A dual-polarized slot antenna for millimeter waves," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 737-737, May 1998.
- [14] J. W. Kooi, J. A. Stern, G. Chattopadhyay, H. G. LeDuc, B. Bumble, and J. Zmuidzinas, "Low-loss NbTiN films for THz SIS mixer tuning circuits," *Int. J. IR and MM Waves*, vol. 19, pp. 373-383, 1998.
- [15] J. Zmuidzinas, J. W. Kooi, J. Kawamura, G. Chattopadhyay, J. A. Stern, B. Bumble, and H. G. LeDuc, "Development of SIS mixers for 1 THz," *Proc. SPIE*, vol. 3357, pp. 53-61, May 1998.